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Research Article

Numerical Simulations of Fog Events in Southern Portugal

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This work aims at improving the knowledge on fog formation and its evolution in the Alentejo region (Portugal). For this purpose, brief regional fog climatology, essentially based on information from the Beja Air Base meteorological station, was produced and several numerical high resolution simulations were performed using the Meso-NH. The ECOCLIMAP database used to generate the model physiography was improved to include the Alqueva reservoir (~250 km^2), filled in 2003. The model results were compared with surface and satellite observations, showing good agreement in terms of fog occurrence and persistence. Various forcing mechanisms for formation, development, and dissipation of fog were identified, confirming the influence of two small mountains that block the moist air from the Atlantic Ocean, preventing the fog from reaching innermost regions. The introduction of the Alqueva large reservoir induces changes in the landscape and environment. The effects of the water vapour addition and of the changes in mass and energy surface fluxes on fog formation and evolution were studied. It was found that the reservoir may have a direct impact on fog formation over the lake and its vicinity. Depending on the large scale meteorological conditions, their influence can be both positive and negative, in terms of spatial coverage and temporal persistence.

1. Introduction

Usually, a fog episode has a large impact on air, maritime, and land transportation, most particularly in aviation. Frequent delays, diversions, and cancellations have various impacts on society. Since visibility is one of the most difficult weather variables to predict, its understanding is crucial. There is the need to apply the latest techniques and approaches to improve the prediction of the formation and evolution of fog. Improved forecasts of fog in terms of location, duration, and variations in visibility have an enormous operational value in the transportation area under reduced visibility conditions, particularly for aviation. In the Alentejo region, in southern Portugal, there are an aeronautical infrastructure located near Beja Town (Portuguese Air Force) and a civilian airport terminal (Beja Airport) that are several times affected by fog events. The first motivation for the development of this work is to better understand this phenomenon in the region and how it forms and develops, in order to optimize techniques to analyse and predict the fog in that aerodrome. The effects on fog of a relatively recent man-made lake, the Alqueva large reservoir, localized in the region, are also discussed.

The fog formation involves several processes, such as cloud physics, aerosol chemistry, radiation, turbulence, the large and small scale dynamics, and surface conditions, including water bodies, topography, vegetation, and soil type. High moisture, condensation nuclei, and cooling processes are the conditions for its formation [1]. It often occurs under stable atmospheric situations during clear sky nights and with light to calm wind. Still, the local influence of these elements can play a vital role in the formation, duration, and intensity of fog events that can be enhanced if air pollutants are present [2].

As mentioned by Cotton and Anthes (1989) "*in the International Cloud Atlas from WMO (World Meteorological Organization)* [3] *Fog is not treated as a separate cloud genus. Instead it is defined in terms of its microstructure, visibility, and proximity to the earth's surface. Therefore, fog is composed by very small water droplets (sometimes ice crystals) in suspension in the atmosphere and reduces the visibility at the earth's surface* *to less than 1000 m*" [4]. The vertical extent of fog ranges between a few meters and several hundred meters. However, the fog can be also considered as a cloud with the base in contact with the surface. Fog may be considered the less dynamic cloud type. The mean vertical velocity in fog is usually small. Typically the liquid water content in fog ranges from 0.05 to 0.2 g/m^3 with lifetimes of 2 to 6 h [4], but it can, in certain circumstances, lasts longer than 24 hours or even several days.

The improvement of fog forecasting in location, duration, and visibility restrictions has an enormous operational value. It is important to understand and diagnose thermodynamics, kinematics, and microphysics of the processes of formation and evolution of fog. The thermodynamic and kinematic components are easily quantified or inferred; however, the microphysical and atmospheric boundary layer processes are not [5]. Fog is a boundary layer phenomenon that typically develops in the surface stable nocturnal atmospheric boundary layer. Its development is strongly influenced by surface conditions, soil cover for fogs over land, and sea state for fogs at sea. Effects of the underlying surface on fogs can be direct when the surface influences the profiles of wind, temperature, humidity, and local circulations through horizontal heterogeneities or indirect through modification of radiative properties of the atmosphere by microphysical processes and varying aerosol spectra [1].

Turbulence and radiative processes play an important role in fog characteristics. They can contribute positively in its formation or negatively leading to its dissipation. For example, the turbulent mixing is an ambiguous but decisive factor in fog formation. If turbulent mixing is too low, dew deposition at the surface will inhibit condensation in the atmosphere and hence inhibit fog formation. If turbulence is strong enough, it may promote condensation in a supersaturated surface layer of sufficient depth and hence lead to fog formation and development [6].

Often, the numerical modeling does not provide a clear answer to the turbulence role, because the results depend on the parameterization used and radiative processes, both loaded with significant uncertainty. The complexity of turbulence and the surface parameterization, as well as the vertical and horizontal high resolutions required, represent a main obstacle to the fog forecasts success in time. Therefore, surface conditions and turbulent flux parameterizations will continue to be an important research topic in fog studies and modeling. One-dimensional models have been developed for operational and research purposes; for example, Teixeira and Miranda combined a suite of parameterizations based on finite element methods for the vertical discretization. The coupling of 1D and 3D models and their integration with observations also lead to promising results in fog prediction. Presently, detailed versions of fog microphysics from 1D models are incorporated into 3D models, allowing improving weather forecasts [7]. The success of numerical modeling and fog prediction depends heavily on the fog type. Some fog events are mainly stimulated by dynamic processes such as advection and orography. If the fog occurrence is dominated by other processes, for instance, radiation, turbulent, or direct interaction between the surface and the atmosphere, then the numerical modeling of the mist may become a very difficult task.

The fog forecasting using operational numerical weather models is usually a very difficult task due to their relatively coarse horizontal and vertical resolutions, causing that operational fog forecast to be usually performed based on empirical rules and statistical methods [7]. However, it is possible to obtain a deterministic three-dimensional fog model modifying existing numerical weather prediction models properly [8]. By increasing the horizontal and vertical resolutions of the grid near the surface and improving significantly the model physical parameterization such as turbulence, heat, and moisture fluxes at the surface, it is possible to represent fog events in realistic way. When using high resolution in the vertical, grid distances in the lowest layers of the atmosphere must be small enough to accurately solve the evolution of physical processes within the atmospheric boundary layer near the surface [9]. The observed fog structure is often irregular, mostly due to horizontal soil and vegetation heterogeneities. To perform realistic fog simulations it is important to have the geographical distribution of soil moisture, vegetation, and water bodies well represented.

The use of numerical weather prediction models in medium and short term fog forecasting for aviation purposes is still a problem that needs continued research. However, they are already implemented in certain airports, such as Charles de Gaulle, Paris [10], and San Francisco, California [11]. These models include precise parameterizations of radiative, turbulent, and surface processes and rely on detailed and continuous near surface observations of temperature, humidity, wind, radiation, and visibility. They produce accurate fog forecasts but their application remains local [12].

In this study, the atmospheric mesoscale Meso-NH is used [13]. The Meso-NH has been successfully used in simulation of fogs over different regions, for example, Cuxart and Jimenez [14] over the Ebro river basin, Spain [14], Bari et al. over Casablanca, Morocco [15], Bergot et al. over Paris, France [16], and Salgado over Alentejo, Portugal [17]. The Meso-NH mod was also used to improve the characterization of the atmospheric circulations in the south of Portugal (e.g., Costa et al., 2010, and Salgado et al., 2015) [18, 19]. In the present work, several Meso-NH simulations of real case studies are used in order to (i) reevaluate the ability of numerical prediction of fog in the region and (ii) characterize typical regional large fog events and discuss the impact of the Alqueva reservoir on fog.

This article is divided into four more sections, as follows. The study domain, the data, and the numerical experiments are described in Section 2, regional fog climatology is presented in Section 3, and the results around the case studies and the impact of the reservoir in fog are discussed in Section 4. The conclusions are presented in Section 5.

2. Materials and Methods

2.1. Study Area. The region under consideration is the Alentejo, located in southern Portugal (about a third of

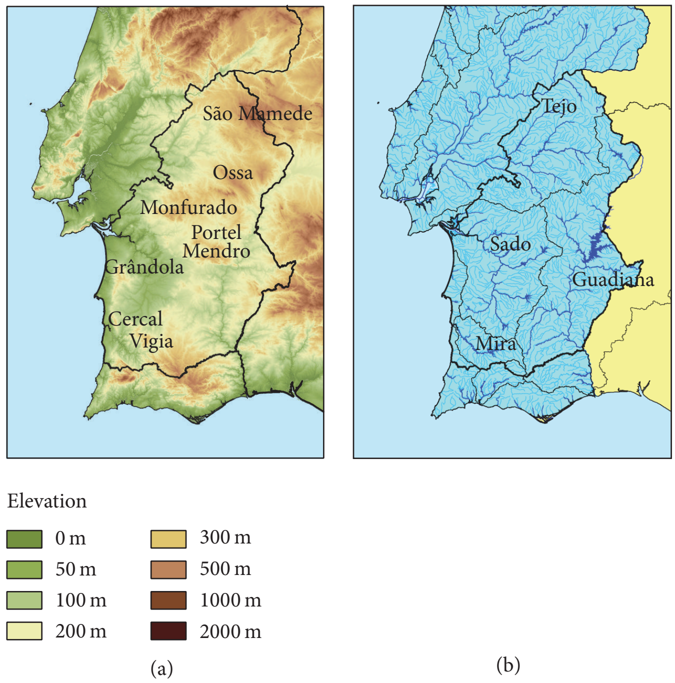


FIGURE 1: (a) Regional orography and main elevations; (b) main hydrographic basins.

the total country area), being limited to the north by the Central Region, to the east by Spain, to the south by the Algarve Region, and to the west by the Atlantic Ocean. The region is crossed by three large river basins (Tejo, Sado, and Guadiana), which greatly influence the fog formation and evolution in the area, especially its major courses and reservoirs. The relief of the region, shown in Figure 1, is characterized by great uniformity of plains, slightly uneven, whose average altitude is around 200 m, only with some mountainous outcrops, undervalued, with the exception of the São Mamede mountain chain (1025 m). However, focus should be given as well to mountains of Ossa, Monfurado, Portel, Mendro, Grândola, Cercal, and Vigia, which appear to have a significant impact on the fog development, particularly in their limits definition.

The Alentejo climate is characterized as Temperate Mediterranean type (Dry Subtropical), with hot, dry summers and rainy and mild winters. The eastward decrease of the maritime influence makes the inland areas particularly hot in summer and relatively cool in winter. The region is mainly influenced by the Atlantic Ocean in the west coastal regions, having a more continental influence in inland areas. Rainfall is weak, being predominant in the winter months. The Alqueva Multipurpose Project centered on the Alqueva dam and its strategic water reservoir at the Guadiana Basin (see Figure 1(b)), which extends for 83 km, covering an area of 250 km^2, with a total storage capacity of 4150 million m^3 located in the Alentejo [28]. The project aims to reinforce the water supply to around 200,000 inhabitants, to create an equipped irrigation area of around 120,000 hectares, to generate clean energy from a hydroelectric power plant (total installed capacity of 520 MW), and to develop regional tourism.

2.2. Observational Dataset. Data collected at the meteorological surface stations indicated and described in Table 1 and shown in Figure 2 were used. It should be noted that, among these stations, only Beja Air Base and Badajoz provide regular observations of horizontal visibility, as they are integrated in airports. However, only Beja Air Base provides aeronautical hourly meteorological observations continuously (24 hours a day) providing data from horizontal visibility, important to evaluate the occurrence of fog events.

Remote sensing data from geostationary orbit satellite (Meteosat: SEVIRI, Spinning Enhanced Visible and Infrared Imager) were used for a comparative event analysis. Data from polar orbiting satellites (TERRA and AQUA: sensor MODIS, Moderate Resolution Imaging Spectroradiometer) were used to obtain the water surface temperature of Alqueva reservoir for events with a lack of in situ observational data. Data from Meteosat-10 presents as main disadvantage the great distance to the Earth's surface, which restricts its spatial resolution (~3 km). The fog (or low clouds) is particularly difficult to detect using only one Infrared Band (IR) channel at night, because this is a very low altitude phenomena and the top of the fog and the surface, in areas without fog, present quite similar Brightness Temperatures (BT) [29].

In this work, two different IR channels, the IR3.9 and the IR10.8, were used. It was possible to detect fog using the BT difference between them. These channels are located in the atmospheric window regions, where the attenuation of the radiation due to absorption by atmospheric gases is not

Table 1: Weather stations used.

Type	Station	Latitude	Longitude	Altitude
I	Portalegre	39° 16′ 59″ N	7° 25′ 01″ W	597 m
I	Évora CC	38° 31′ 59″ N	7° 54′ 00″ W	245 m
I	Beja Town	38° 01′ 01″ N	7° 52′ 01″ W	246 m
I	Sines	37° 57′ 00″ N	8° 52′ 01″ W	98 m
II	Beja Air Base	38° 04′ 01″ N	7° 55′ 01″ W	194 m
II	Badajoz Talavera La Real	38° 52′ 59″ N	6° 49′ 59″ W	185 m

Type I: Synoptic Meteorological Station (Manual/Automated).
Type II: Synoptic Meteorological Station/Aeronautic (Manual/Automated).

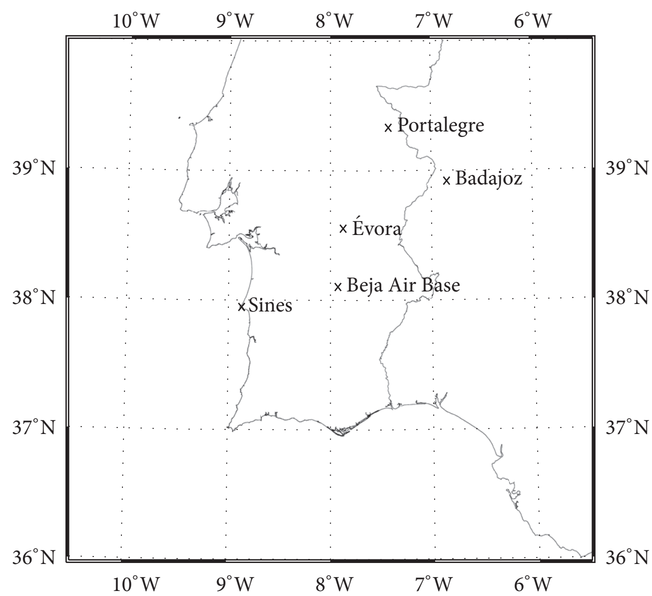


Figure 2: Meteorological stations in model domain 1.

significant. However, the emissivity of liquid water (case of fog) is smaller in the IR3.9 channel than in the IR10.8, and thus the fog BT will be lower in the IR3.9 overnight. Despite the fact that the emissivity of liquid water is lower in IR3.9, during the day, the reflected solar component is substantially greater in IR3.9, so the radiance in the IR3.9 channel is greater than in the IR10.8. These differences are very useful in fog identification, especially at night because during the day the VIS channels are available and allow better fog detection [30, 31]. RGB composites were also used in the fog detection, during both the night and day time. At night the RGB composite, Night Fog-RGB, uses channels 4 (3.9 μm), 9 (10.8 μm), and 10 (12.0 μm) of SEVIRI sensor. This product is only useful during the night; the main limitation is the fact that a thin layer of Cirrus can be enough to obstruct the fog or low stratus detection. During the day the Natural RGB was used, which is based on two channels of VIS, channel 1 (0.6 μm) and channel 2 (0.8 μm) of SEVIRI sensor, and one channel in the near infrared (NIR), channel 3 (1.6 μm).

2.3. Model Setup. The mesoscale atmospheric modeling system used was the Meso-NH [12] developed by CNRM (Météo *France*) and *Laboratoire d'Aérologie*. It is a nonhydrostatic anelastic numerical model, able to simulate the atmospheric motions, ranging from synoptic scale (hundreds of kilometers) to microscale (tens of meters), with a comprehensive physical package and an ensemble of facilities to prepare initial states, either idealized or interpolated from real meteorological analyses or forecasts. The version used in this work was the MNH-V4-9-3. The Meso-NH physical package includes several parameterization schemes to represent surface-atmosphere interactions, radiation, turbulence, clouds and precipitation, convection, atmospheric electricity, chemical reactions, and aerosols. For these processes, different parameterization options are available, which can be enabled or disabled depending on the study to make. The schemes activated in the present work are listed in Table 2. The microphysics scheme used in the simulations was the adopted scheme in the regional numerical weather prediction model of Météo France, the AROME, which is running operationally, two times per day, at the Portuguese Institute of Sea and Atmosphere to forecast the weather in Portugal.

This work was carried out launching simultaneous simulations on different scales using a two-way grid nesting technique [30, 31] in order to perform a further study in the

Table 2: Adopted features for the final Meso-NH simulations.

Domain	D1	D2
Discretization	Nx = Ny = 150 Dx = Dy = 3 km	Nx = Ny = 120 Dx = Dy = 1 km
	Nz = 55 (sigma coordinates) Dz (5 m) = 10 m; Dz (500 m) = 50 m; Dz (5 km) = 650 m; Dz (25 km) = 2000 m	
	Dt = 6 s	Dt = 2 s
Central point	Latitude: 38° 00′ N; longitude: 008° 00′ W	Latitude: 38° 22′ N; longitude: 007° 36′ W
Surface-atmosphere interactions.	ISBA [20] TEB [21] ECUME [22] Flake [23]	
Physics schemes	Radiation: ECMWF [24] Turbulence: Quasi-1D (on the vertical) [25] Clouds microphysics: ICE3 [26] No convection	
Horizontal visibility	Kunkel [27]	

areas of interest. Two domains were considered (see Table 2 for details). Surface schemes that improve the numerical simulations at the atmosphere lower levels are available in the Meso-NH, providing more realistic lower boundary conditions. These schemes are grouped on a surface model platform, called SURFEX (*Surface Externalisée)* [32]. The SURFEX platform includes the ISBA (Interaction Soil-Biosphere-Atmosphere), a land surface model [20] with 3 soil layers by default, the Flake (Freshwater Lake) 1D inland water model developed by Mironov et al. [23] and integrated in SURFEX by Salgado and Le Moigne [33], the TEB (Town Energy Balance) developed by Masson [21] in order to compute the fluxes over urban areas, and the ECUME (Exchange Coefficients from Unified Multicampaign Estimates) parametrization of sea surface fluxes [22]. Finally the Kunkel formulation provides the surface visibility parameter from the relationships between extinction coefficient and liquid water content [27].

In the present study, the simulations were performed using 6 hourly analyses from the ECMWF operational model (IFS, Integrated Forecasting System) with 0.125 degrees of horizontal resolution, as initial and boundary conditions. The model was configured with two nested horizontal domains by two-way interaction. The largest domain (D1) has a grid with 150 × 150 points, a spatial resolution of 3 km (450 × 450 km), and it is centered at the coordinates latitude, 38° 00′ N, and longitude, 008° 00′ W; the smallest area (D2) has a grid with 120 × 120 points, a spatial resolution of 1 km, and it is centered approximately at the following coordinates: latitude, 38° 22′ N, and longitude, 007° 36′ W. The latter are chosen in order to further study the region that includes the Alqueva reservoir and the Beja Air Base. The simulation domains can be seen in Figure 3, which depicts the orography used. Various vertical grids were tested, as several studies indicate its influence in fog modeling like PARISFOG Campaign [5]. After some tests, a vertical grid with 55 levels, with the lowest level at 5 m above the surface, was adopted. The temperature of the water surface at Alqueva reservoir was initialized by the temperatures obtained from MODIS satellite data, and the Flake model was activated.

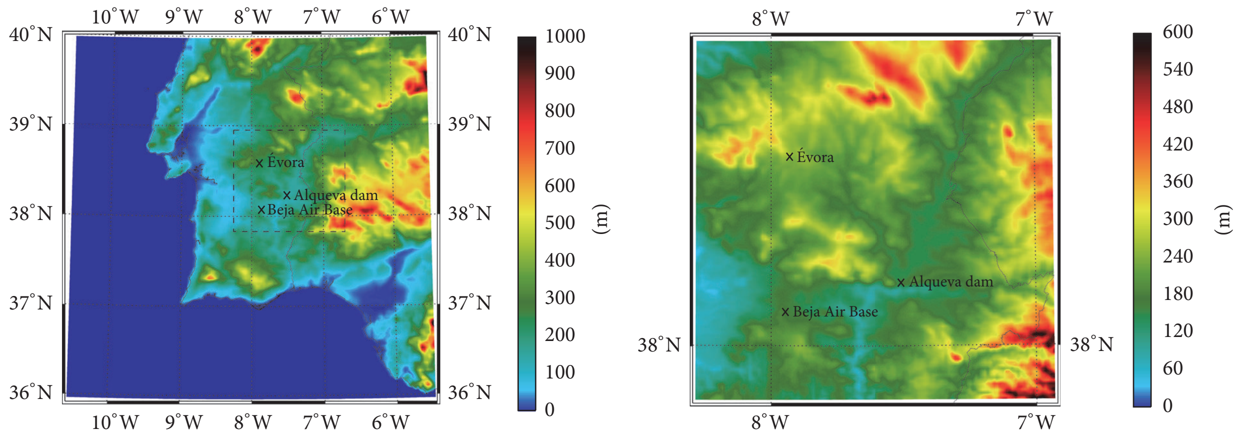
Due to the complexity of the atmospheric system and its relations with the surface there is an increasing need to accurately represent the surface and the processes occurring therein and that significantly contribute to the interaction with the atmospheric boundary layer. Thus, there is a need to have a thorough and realistic description of the land surface characteristics in meteorological models, from mesoscale research and numerical weather prediction models to general circulation models [34]. The surface schemes need the right allocation of the land-water mask and of the soil-vegetation characteristics for the surface fluxes calculation of momentum, heat, and moisture. It is necessary to use some databases in order to provide the soil characteristics and vegetation cover [34]. In Meso-NH, the physiographic fields are created from specific data contained in the following global databases: ECOCLIMAP_v2.0 [34] for surface cover, GTOPO30 [35] for orography, and Clay and Sand databases derived from FAO [17].The databases have a horizontal resolution of 30 arc sec (~1 km).

The ECOCLIMAP database developed in the Météo France was created in order to provide the necessary surface parameters for soil-vegetation-atmosphere transfer models. This was produced from the combination of several other databases, such as the surface use, vegetation index, or soil texture maps. The GTOPO30 database is a global digital model representing the elevation of the terrain (Digital Elevation Model, DEM) and results from work led by the US Geological Survey's (USGS) EROS (Earth Resources Observation and Science) Data Center.

2.4. Landscape Changes. Despite its very recent review, the ECOCLIMAP v2.0 database lies with outdated data for the Alentejo region, including the area occupied by the Alqueva reservoir and other inland lakes created after the lake was filled up. To run the simulations with greater realism, it was necessary to make certain amendments in the existing surface parameters. The changes introduced in the inland water cover in the region can be seen in Figure 4. It was assumed that the reservoir is at its full storage level, corresponding to an elevation of 152 m above the mean sea level. This modification represents better the actual surface cover and is needed in order to study the possible impact of the Alqueva reservoir in relation to fog events [17].

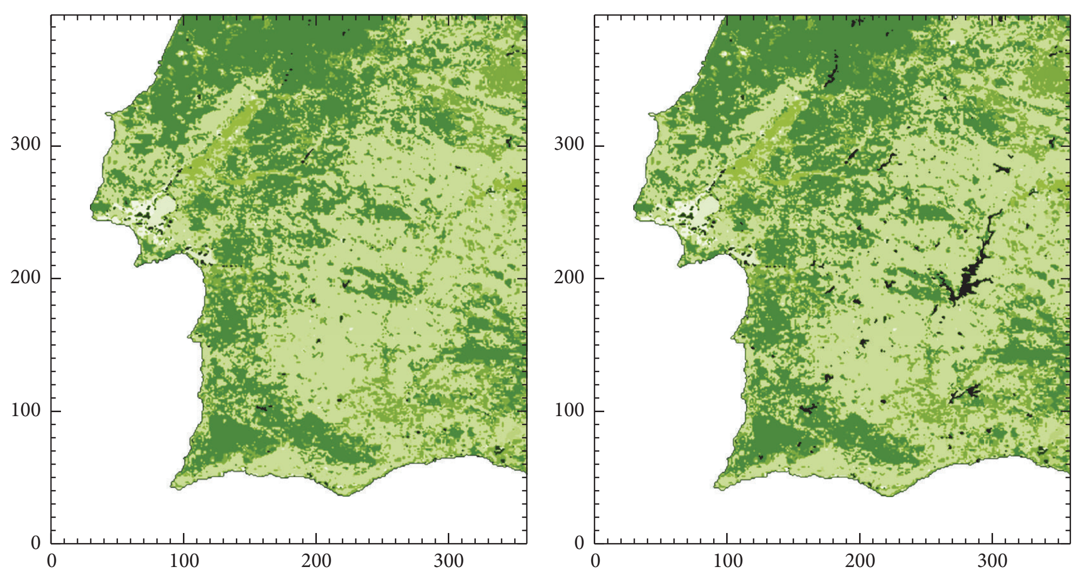
Due to changes in the ECOCLIMAP database, it was also necessary to change the orography in GTOPO30 for Alqueva reservoir area due to its large dimension. The value of 152 m (full storage level) was imposed over the numerical flooded area.

2.5. Cases Studies Selection. The period considered for the case studies selection was between December 2012 and July 2013. In Beja Air Base, 47 fog events were registered during this period. Among these, five events were selected (see in Table 3) because they present different weather patterns,



(a) (b)

Figure 3: Orography of domains D1 and D2.



(a) (b)

Figure 4: ECOCLIMAP v2.0 database: (a) original and (b) changed. Green colors (mean nature) and black colors (mean surface water bodies). Axis coordinates are in km.

considerable persistence, significant horizontal extension, and lack of high clouds, which allowed for using satellite observations. The first three cases occur in winter and are characterized as radiation fogs; the latter two occur in summer and are best characterized as advection and orographic fogs. Among the five simulated events, two will be discussed here in detail (Section 4): one winter case of radiative fog (23/12/2012) and one summer case of advection fog (18/07/2013). All the 5 simulations are used in Section 4.3 to access the impact of the Alqueva reservoir on fog.

3. Regional Fog Climatology

In the Alentejo region, the radiation fog occurs mainly in winter and the advection fog in the remaining seasons. Nevertheless, there are also frequent episodes of orographic fogs, particularly due to obstruction by the hills.

In winter, fogs in the Iberian Peninsula mainly occur during anticyclonic blocking situations that promote pronounced nocturnal cooling, especially in the inner regions. Fog is formed particularly in the vicinity of rivers, valleys, and lakes. In the remaining seasons, advection fogs mainly occur in coastal regions, under the influence of the Azores Anticyclone, especially when extending in ridge over the Iberian Peninsula. The dynamics associated with stable anticyclonic circulation also causes the fog occurrence in windward slopes, which sometimes blocks the transport and the fog evolution into the region, despite its small elevations.

Frontal fogs also occur occasionally in Alentejo region, especially in winter season, under sustained rainfall situations

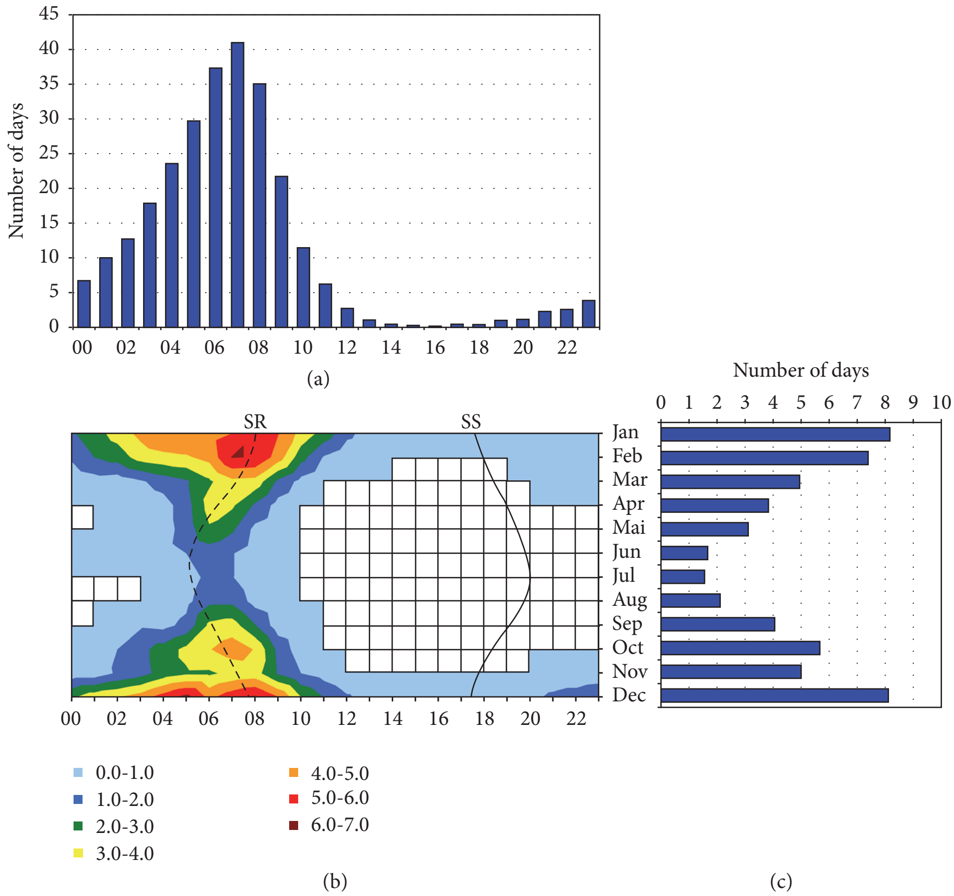


Figure 5: Mean number of days with fog over the entire year in Beja Air Base (2006–2012) by (a) hour, (b) hour and month, and (c) month. Hours in UTC. SR: sunrise; SS: sunset.

Table 3: Simulation periods for the selected case studies.

Date	Simulations	Study periods
2012-12-08	07 18:00–08 18:00 UTC	07 21:00–08 15:00 UTC
2012-12-23	22 18:00–23 18:00 UTC	22 21:00–23 15:00 UTC
2013-02-05	04 12:00–05 18:00 UTC	05 00:00–05 15:00 UTC
2013-07-16	15 18:00–16 12:00 UTC	15 21:00–16 12:00 UTC
2013-07-18	17 18:00–18 12:00 UTC	17 21:00–18 12:00 UTC

from warm fronts moving slowly, with southwest/westerly light wind and sometimes with drizzle. This type of fog occurs mainly during the night. Fog events in the warm sector of frontal systems during the night due to the lowering of low cloud bases are also reported. Fog may also develop in postfrontal cold air in winter, during dawn and early morning, due to noticeable nocturnal cooling, especially after large frontal precipitation and under light winds due to weakening of pressure gradient.

A more detailed description of fog occurrence in Beja is possible, based on information from Beja Air Base meteorological station. Figure 5 shows the distribution of the average number of foggy days per month and hour over the entire year between 2006 and 2012 (there is only a complete hourly series since 2006), with the distribution of average number of foggy days by hour (a) and the average monthly number of days with fog (c). From the analysis of Figure 5, it can be concluded that fogs in Beja Air Base occur more frequently in winter season (December, January, and February) and mostly between 04 and 10 UTC, with more than 20 days with fog at these times, and the maximum value is at 07-08 UTC (more than 40 days per year of fog). It should be noted that the number of days with fog is greater next to the indicator line of monthly average sunrise time. Figure 5 also suggests that the fog events, which occur during the winter months, are longer compared to those occurring in the rest of the year.

Figure 6 shows the distribution of the monthly average number of days with fog through the year for two periods 1994–2002 (before Alqueva dam concluded) and 2003–2012 (after Alqueva dam concluded). It can be seen in Figure 6 that the fog events occur most frequently during the months of winter (December, January, and February) at Beja aerodrome, with more than seven days on average during 2003–2012. When comparing the two periods, it seems that there is an increase in the average number of days with fog in the winter months (December and January, about 4 days in total) and an appreciable decrease in May, July, and August (about 4 days in total). As mentioned before, in winter the fogs in the region

Table 4: Mean absolute error (MAE) from the comparison between observed data and its simulations (Cases II and V).

Variable	23/12/2012		18/07/2013	
	Bias	MAE	Bias	MAE
Temperature (2 m) [°C]	0.1	1.6	2.9	2.9
Relative humidity (2 m) [%]	−0.3	3.2	−9.26	10.2
Wind speed (10 m) [m/s]	−1.0	0.7	0.2	0.8
Wind direction (10 m) [°]	−1.4	11.7	−19.2	28.0

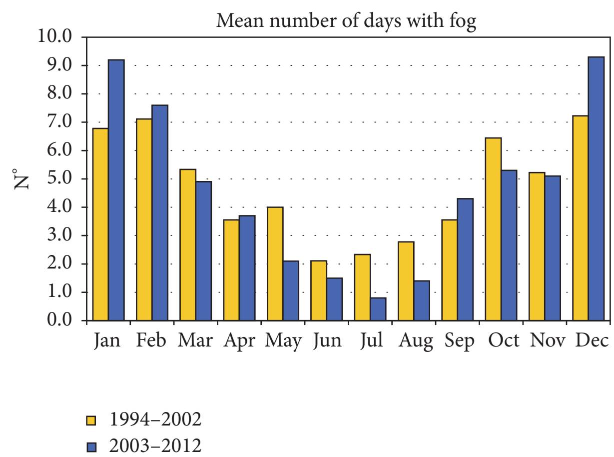


Figure 6: Monthly mean days of Fog in Beja Air Base in the periods 1994–2002 (yellow) and 2003–2012 (blue).

are frequently of radiative type, which highly depends on the local surface conditions. Thus, the data shown in Figure 6 suggest the existence of a slight impact caused by Alqueva in the increasing of the average number of foggy days in Beja aerodrome during winter. On the contrary, the decrease in the average number of foggy days in late spring and summer cannot be attributed to a specific regional effect, being mainly due to synoptic scale weather systems, unlike winter events that are often due to local effects.

4. Results and Discussion

4.1. Comparison between Observations and Simulations (Beja Air Base). The verification of simulated fog on a numerical grid (nearest neighbour grid point) against single point observations is not easy, especially in situations where the observations are made at locations in the fog limits. Anyway the results obtained from the Meso-NH simulations were compared with data taken at Beja Air Base meteorological station. The mean bias and the mean absolute error for the cases of 23/12/2012 and 18/07/2013 can be seen in Table 4.

From the comparison between the hourly data observed in the Beja Air Base and the simulated data, it can be concluded that the model satisfactorily simulated various parameters: wind speed and direction at 10 m; air temperature at 2 m; relative humidity at 2 m. The values found in Table 4 are comparable with other published state-of-the-art mesoscale simulations, as documented by Schlünzen et al. [36], based on the analysis of 80 journal articles published from 2000 in refereed journals that summarize evaluations of several models or of several model set-ups for one and the same case, focusing on surface measurements. The less good results concerning temperature and relative humidity in Case V are essentially due to the fact that model has anticipated, in about three hours, the fog dissipation over Beja. In a summer day this anticipation has a great impact in the daily mean bias on near surface air temperature and consequently on relative humidity.

With regard to fog, in the winter case there was a very good representation of fog, in its formation, evolution, and dissipation. There was a considerable similarity between the various parameters, emphasizing the horizontal visibility (see Figure 7(a)). In the summer case, the formation of fog was also well represented, but the model anticipated the dissipation in about 2 hours (see Figure 7(b)). The analysis of Figure 7 shows that the simulation of winter case had the best results. In general the remaining cases also showed reasonable results.

4.2. Results

4.2.1. Winter Case (23/12/2012). Regarding the winter case, using surface and satellite observations, it was found that around midnight an event of fog was established in the valleys of the Guadiana and Sado rivers, persisting for approximately 7 hours. After sunrise, with the increase of solar radiation, the areas of higher altitudes start to warm, and the fog remains only over the wetlands, especially in northern areas

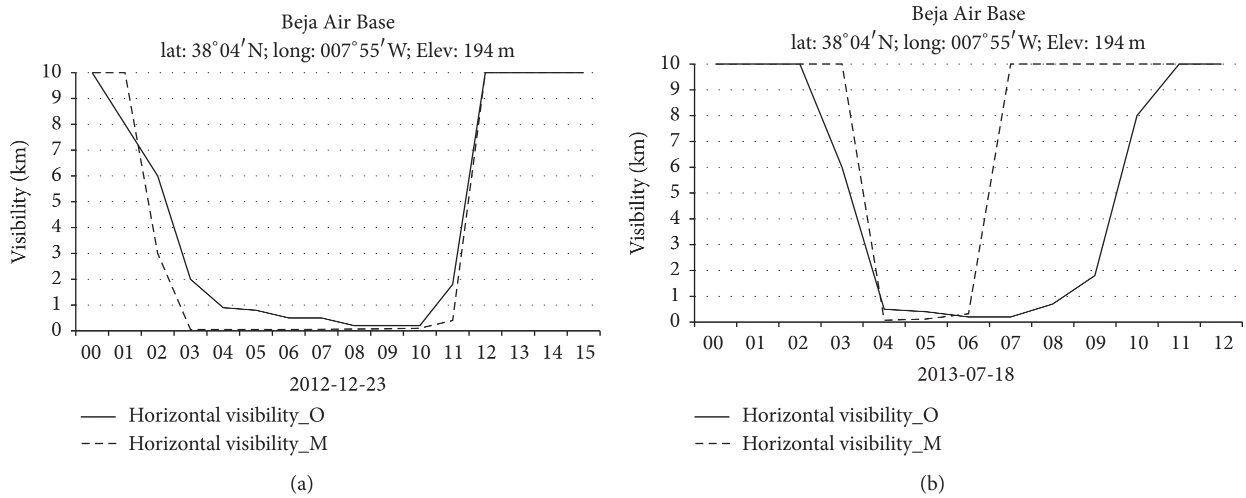


Figure 7: Comparison between the horizontal visibility observed and simulated data (D02) at Beja Air Base in (a) 23/12/2012 and (b) 18/07/2013. UTC hours.

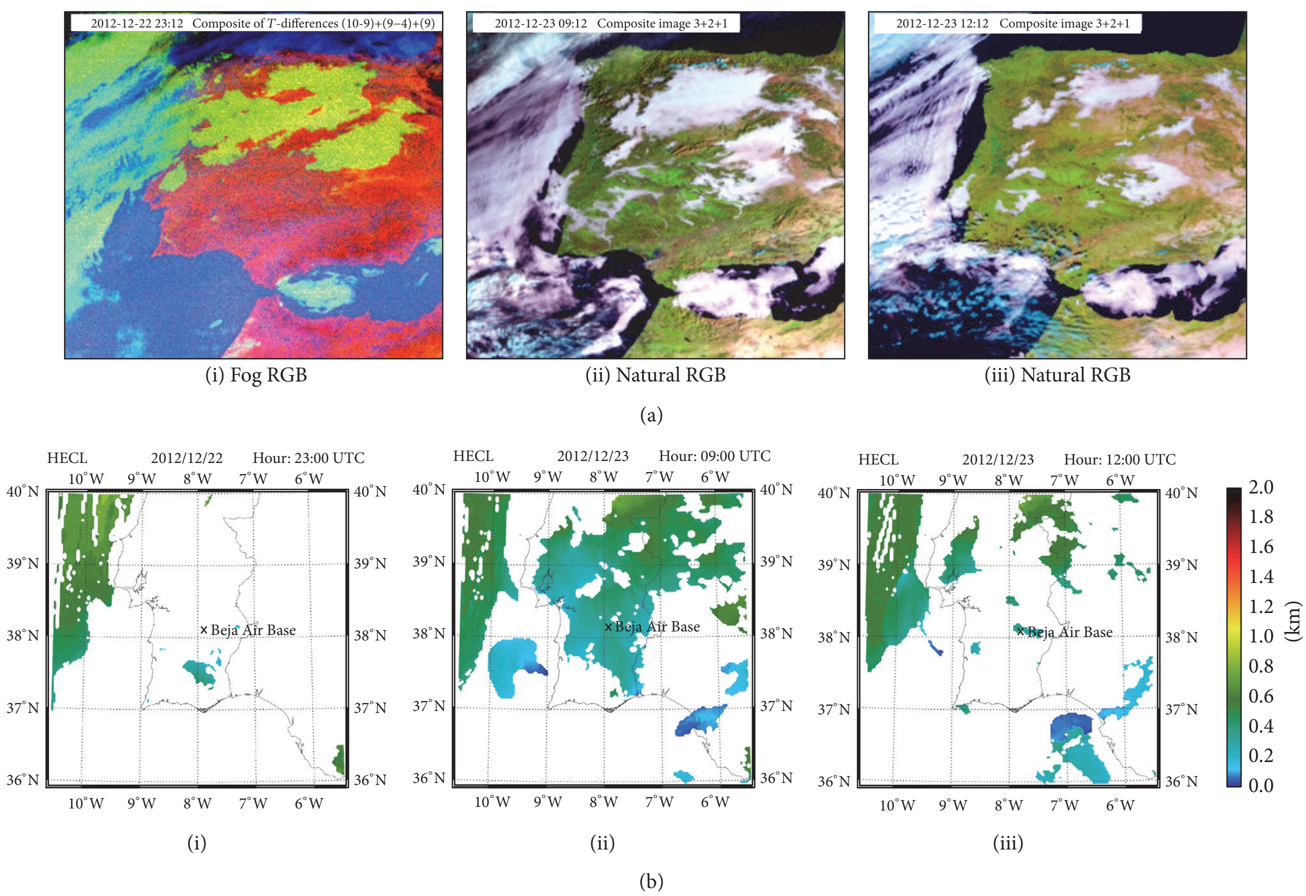


Figure 8: (a) Sequence of satellite images in 22/12/2012 at 23:12 UTC and in 23/12/2012 at 09:12 and 12:12 UTC of 23/12/2012; (b) simulation of explicit cloud top height from the surface in 22/12/2012 at 23:00 and in 23/12/2012 at 09:00 and 12:00 UTC in D1 domain.

of Alqueva reservoir, where there are still some places with fog or low clouds in the early afternoon (see Figure 8(a)). The cloud top height given by the Meso-NH simulations (see Figure 8(b)) indicates the development of low cloud cover around 23 UTC of 22/12/2012 in some areas of southern Alentejo, sprawling its occupation over the entire region before sunrise time, especially in the inland regions. After the sun rise and with the increased solar radiation, the clouds begin to dissipate, persisting, however, some low clouds during the early afternoon.

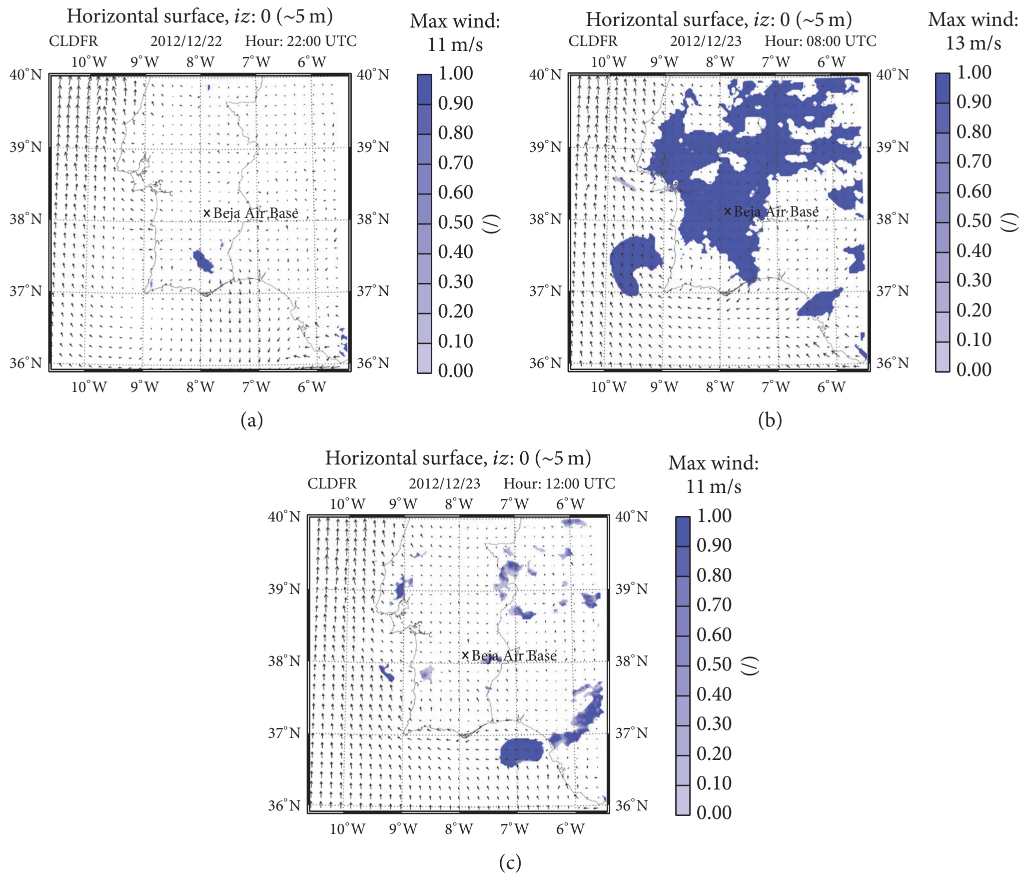


Figure 9: Simulation of cloud fraction (fog, blue scale) and flow (vectors) at 5 m height from the surface, at 22:00, 08:00, and 12:00 UTC in D1 domain.

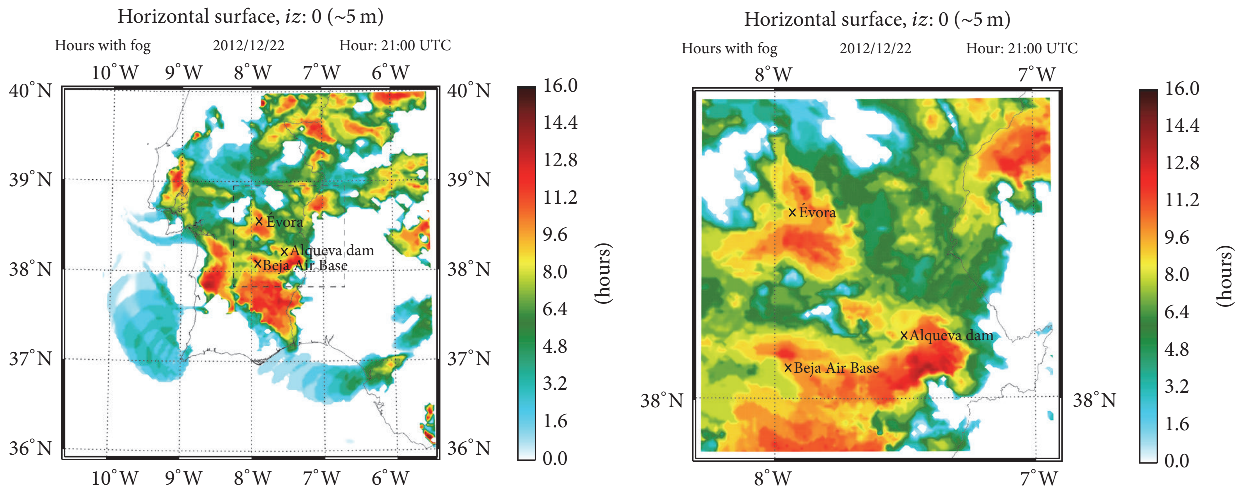
In this case, the simulated fog occurs too early in southern regions (see Figure 9(a)). In late dawn, fog occupies almost the entire region of Alentejo, especially in the interior, except over the highs of São Mamede, Ossa, and Monfurado (see Figure 9(b)). With increased solar radiation after sunrise, the fog begins to dissipate, persisting in a few places around 12:00 UTC (see Figure 9(c)). Figure 9 also shows the horizontal flow at the lowest level of the model, showing that the flow from south-southeast regulates how the fog acquires its shape, being especially installed in the windward sides of the elevations. This is evident, especially in the initial phase of the formation of fog.

Figure 10 shows the number of hours with fog simulated in both domains. In the domain (D1) it may be seen that near the Cercal Hill and in the Guadiana Basin south of the Mendro Hill there were several areas where the fog rested for more than 12 hours. In the inner domain (D2) it is visible, with better details, the increase of fog in southern areas of Alqueva reservoir, with several locations with more than 14 hours of fog. In Beja Air Base the fog lasted about 9 hours.

In Beja Air Base, according to the Meso-NH simulation the fog formation occurs about 02:00 UTC (see Figure 11). The fog quickly acquires a thickness of 100 m, so that the base of the thermal inversion is high and reaches about 200 m at 11:00 UTC. After that, the dissipation of fog begins. After the dissipation of fog, low clouds do not appear to persist.

4.2.2. Summer Case (18/07/2013). There was a progressive cloudiness invasion formed over the Atlantic Ocean immediately following the sunset of July 17th as shown in Figure 12. There is a widespread occupation by low clouds (potentially fog), covering almost the entire region throughout the morning. Only at about 12:00 UTC, the entire region was free of cloud cover (see Figure 12(a)(iii)). The simulated cloud top height field (Figure 12(b)) shows the appearance of low cloudiness along the coast as early as 21:00 UTC and the occupation of much of the region, with advancing night and morning. After sunrise this cloudiness starts to dissipate, so that at 12:00 UTC the entire region is cloudless. In this case, the simulation of cloudiness compares quite well with satellite observations, even though the model underestimates the cloudiness in particular over the northern regions of Alentejo.

The simulations indicate the appearance of relatively small areas of fog in Alentejo around 02:00 UTC (see Figure 13(a)). With its progression after sunrise, fog occupies more inner areas, however not so generalized as suggested by the cloud cover simulations (see Figure 13(b)). After sunrise, fog dissipates quickly, covering at 08:00 UTC only a small



(a) (b)

FIGURE 10: Simulation of the "number of hours with fog" in both domains, between 21:00 and 15:00 UTC.

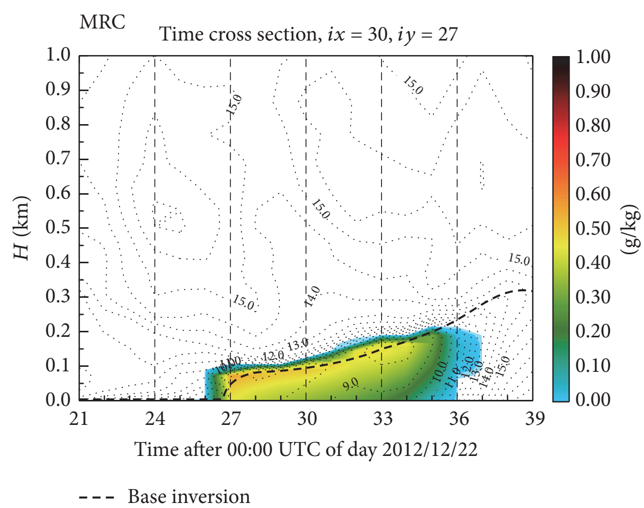


FIGURE 11: Temporal evolution (from 22/12/2012 at 21 UTC to 23/12/2012 at 15 UTC) of simulated air temperature (lines in °C) and liquid water mixing ratio (color scale in g/kg) over Beja Air Base nearest grid point of D2 domain. Fog > 0.05 g/kg liquid water mixing ratio (Introduction chapter).

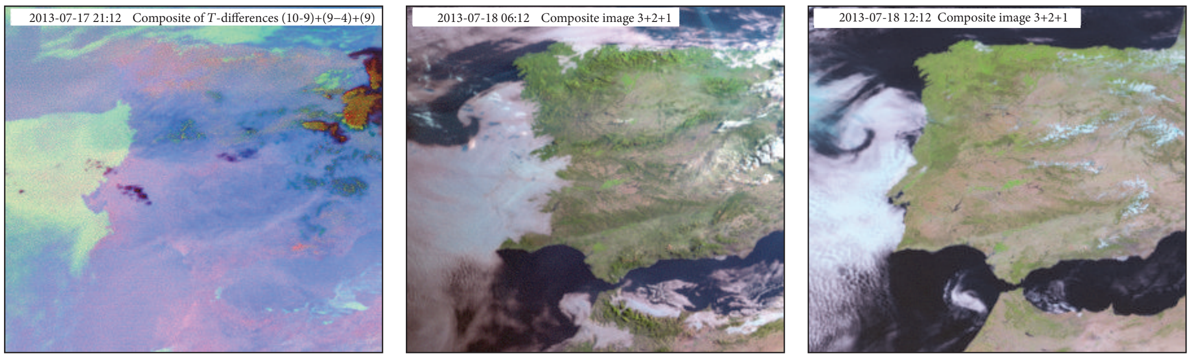
area near the mouth of the Sado River (see Figure 13(c)). According to the model, at 09:00 UTC the whole region was free of fog. Figure 13 also shows the horizontal wind field at the lowest level of the model, which indicates that the predominant westerly flow drives the fog pattern that settles more in the windward sides of the elevations.

Figure 14 shows the number of hours with simulated fog in both domains. In the D1 domain it can be seen that, near Grândola Hill, fog remained in some places more than 8 hours, but in the rest of the domain the residence time of fog did not exceed three hours. In the D2 domain, with better details, an enhancement of fog in an area southwest of Beja Airbase can be seen, where fog lasted over 4 hours, as well as along Mendro, Monfurado, and Ossa Hills. According to the model, some places presented about three hours of fog. Once again, it appears that, beyond the effect of advection, the orography is also an important factor in the formation of fog. In Beja Airbase, the fog lasted nearly 3 hours (see Figure 14(b)).

In this case, simulations suggest that fog does not reach the region of the Alqueva reservoir due to orographic blocking, especially by the Mendro and Portel Hills.

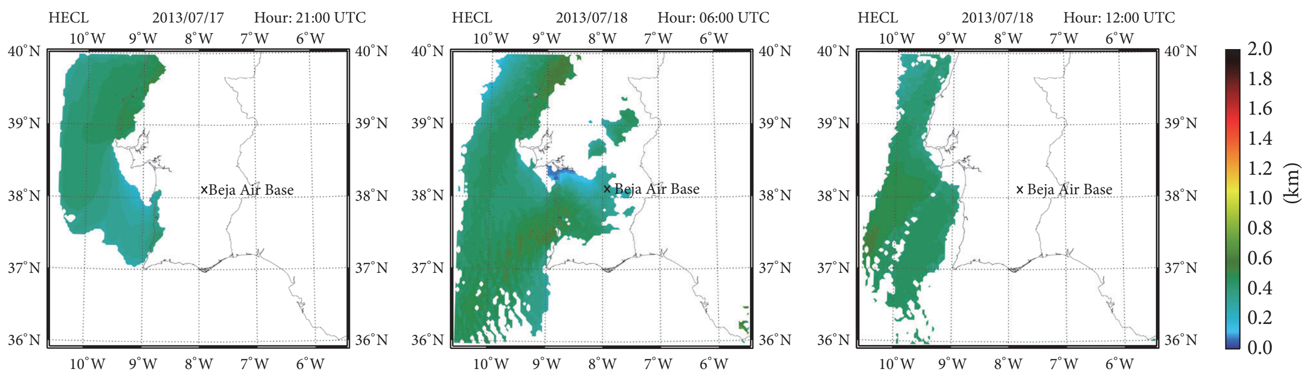
According to the simulation, in the Beja Air Base, fog occurred between 03:00 and 07:00 UTC. With the fog development, the thickness of fog increased. After its dissipation, low clouds (stratus) persisted for several hours as seen in Figure 15.

4.3. Influence of Alqueva Reservoir. In order to investigate the influence of the Alqueva reservoir on fog, simulations were performed with (ALQ) and without Alqueva (PRE-ALQ), for



(i) Fog RGB (ii) Natural (iii) Natural RGB

(a)



(i) (ii) (iii)

(b)

Figure 12: Sequence of satellite images in 17/07/2013 at 21:12 UTC and in 18/07/2013 at 06:12 and 12:12 UTC; (b) simulation of explicit cloud top height from the surface in 17/07/2013 at 21:00 UTC and in 18/07/2013 at 06:00 and 12:00 UTC in D1 domain.

the case studies considered in this work. The impact of the water body is assessed by the differences between the results of both simulations.

In Case I, referring to the 08/12/2012, there are no significant differences in fog occupation in the Alentejo region. However, the simulations indicate a negative difference over the Alqueva reservoir, suggesting that the presence of the water body inhibited the formation of fog over it, probably due to the higher water surface temperature. This is evident from the difference between the simulated number of hours with and without Alqueva (see Figure 16(a)). As shown, over the reservoir, there is a negative difference of 2 to 3 hours, reaching, locally, differences greater than 4 hours.

The results of Case II simulations also indicate that there are no major differences on fog distribution at the regional scale (not shown) and also show negative differences over and in the vicinity of the Alqueva reservoir, suggesting, as in Case I, that the presence of the lake inhibited the fog formation over the lake, probably due to higher temperatures of the water surface. This can be noticed especially in the northern part of the reservoir (see Figure 16(b)).

On the contrary, in Case III (05/02/2013) the results show that over the reservoir, particularly in the south, there are more places, with positive difference of 1 to 2 hours, suggesting that in this case the reservoir had a positive impact. The model shows also positive differences southwest (downstream) of the dam, suggesting that water vapour originated by the reservoir may have been advected to these zones and thus have increased the persistence of the phenomenon. These positive differences may be related to the fact that the flow was less intense when compared to the two previous cases, which favours water vapour availability for condensation (see Figure 16(c)).

For Cases IV and V (16 and 18/07/2013), summer cases, there were no significant differences between simulations with and without Alqueva, due to the fact that they correspond to events of advection fog, originated in the Atlantic Coast, and that the have not reached Alqueva reservoir.

5. Conclusion

A description of fog occurrence near the Alqueva dam was made, based on information from Beja Air Base meteorological station. It can be concluded that fogs in Beja Air Base occur more frequently in winter season (December, January, and February) and mostly between 04 and 10 UTC, with more

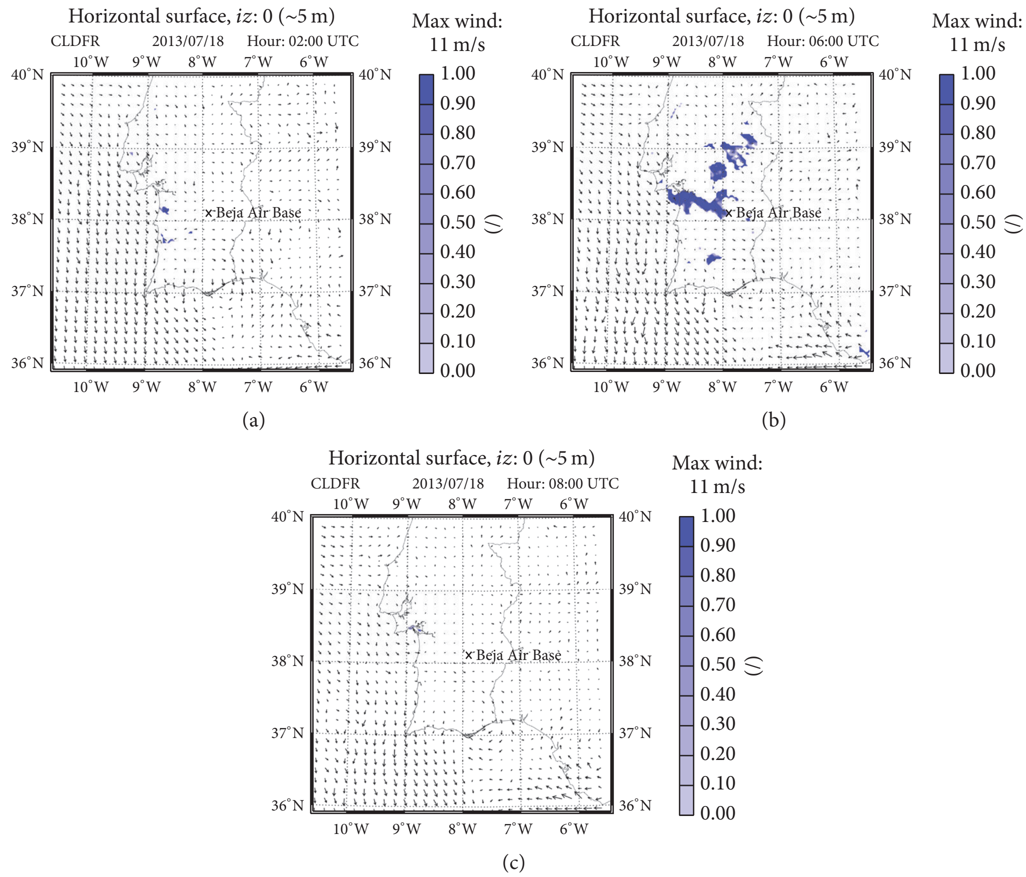


FIGURE 13: Simulation of cloud fraction (fog, blue scale) and flow (vectors) at 5 m height from the surface at 02:00, 06:00, and 08:00 UTC in D1 domain.

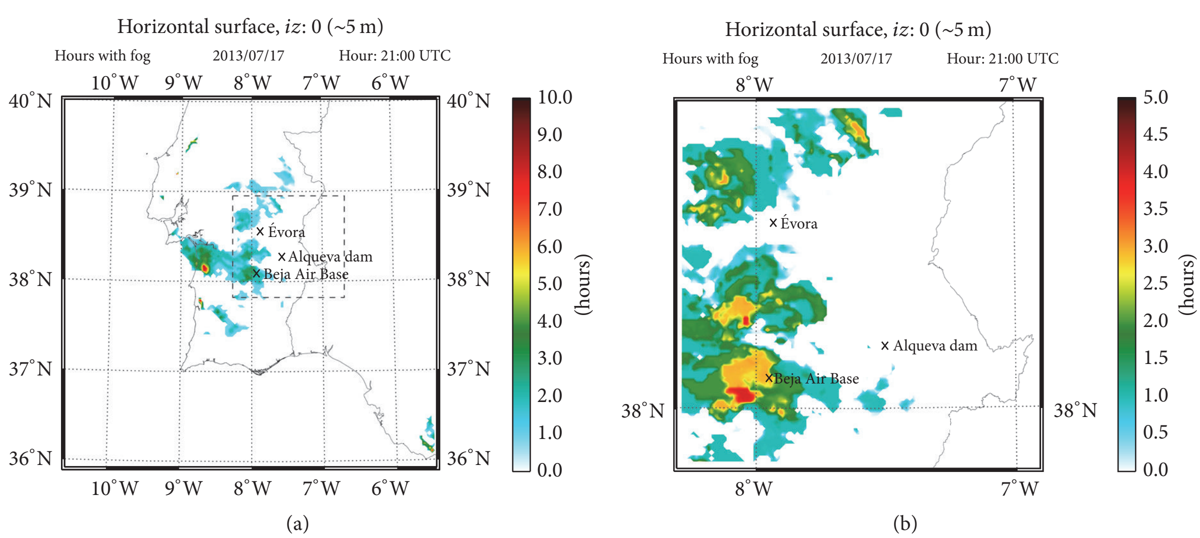


FIGURE 14: Simulation of the "number of hours with fog" in the two domains, between 21:00 and 12:00 UTC.

than 20 days with fog at these times and the maximum value at 07-08 UTC (more than 40 days per year of fog). It can also be stated that the fog events, which occur during the winter months, are longer compared to those occurring in the rest of the year.

To run the Meso-NH over the region it was necessary to update the ECOCLIMAP database, introducing the Alqueva and other smaller reservoirs, not present at the ECOCLIMAP v2.0. In the improved ECOCLIMAP database it was assumed that the reservoirs are at their full storage level.

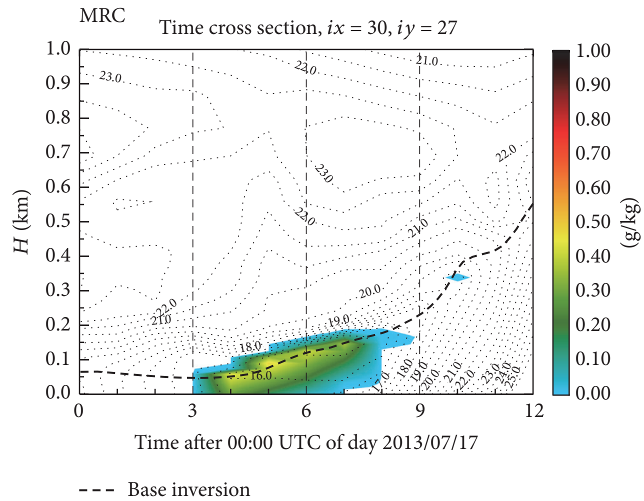
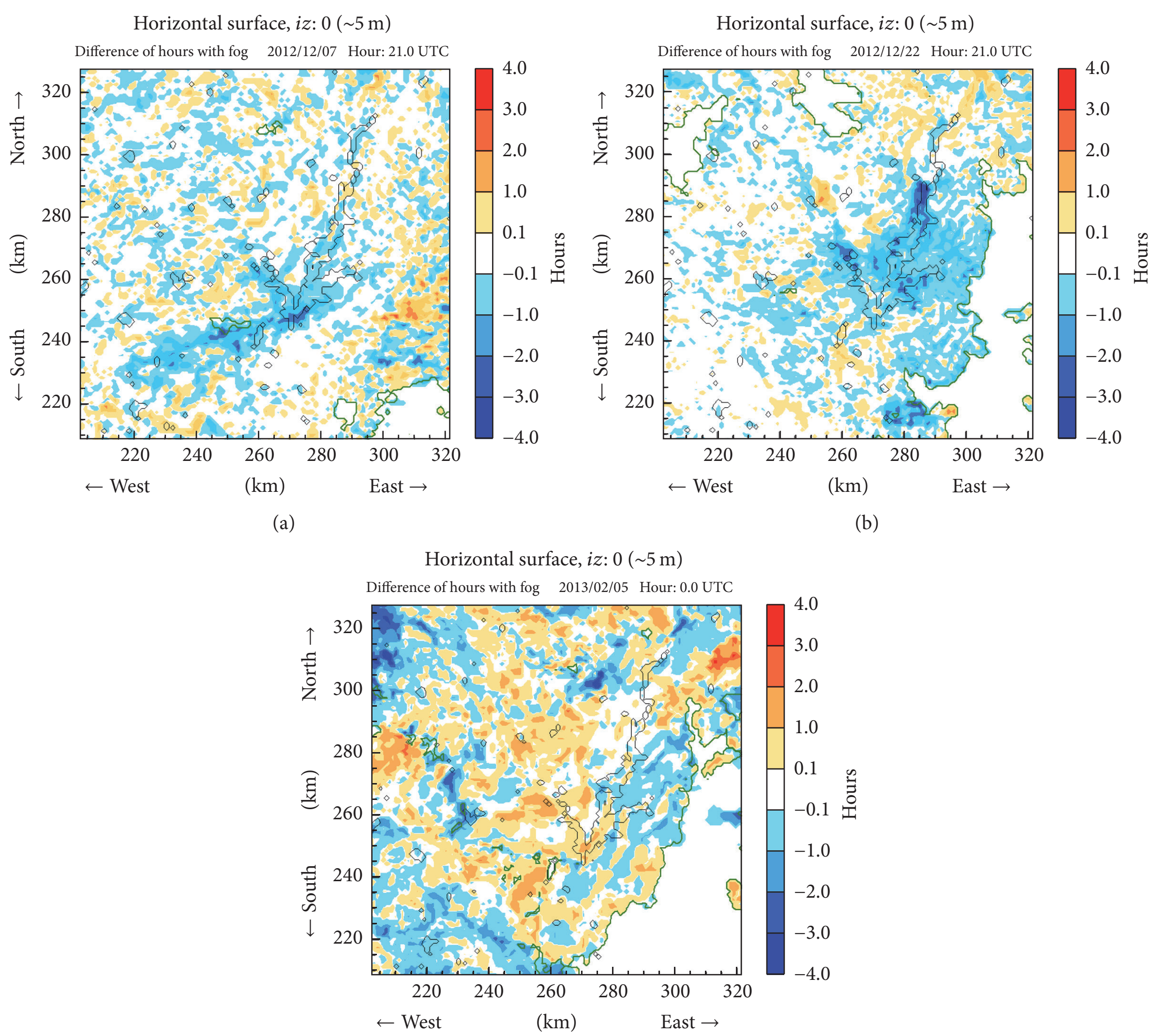


Figure 15: Temporal evolution (18/07/2013 from 00 to 12 UTC) of simulated air temperature (lines in °C) and liquid water mixing ratio (color scale in g/kg) over the Beja Air Base nearest grid point of D2 domain. Fog > 0.05 g/kg liquid water mixing ratio (Introduction chapter).



(a)

(b)

(c)

Figure 16: Difference between the "number of hours with fog" of simulations, with and without Alqueva from 21:00 to 15:00 UTC in D2 domain. Fog occupation boundaries with Alqueva (green line), color scale (Alqueva, original). (a) 2012/12/08, (b) 2012/12/23, and (c) 2013/02/05.

The numerical fog simulations done in this work show different results depending on the different influences exerted by several factors in the region. In winter cases, the fog occurred mainly due to night-time radiative cooling. In summer cases, fog is in general due to advection from ocean or caused by air elevation and adiabatic cooling. The examination of the simulations based on the ECMWF model analyses showed that there was a good similarity between the cloudiness patterns obtained and the corresponding satellite observations.

The horizontal flow near the surface determines how the fog progresses along the simulations, showing that the orographic influence is present in the cases shown, confirming the enormous influence of Mendro and Portel Mountains that block the moist air from the Atlantic Ocean, preventing the fog to reach innermost areas.

As a first observational evidence of the influence produced by the Alqueva reservoir, the distribution of the average monthly number of days with fog through the year for two periods 1994–2002 (before Alqueva) and 2003–2012 (after Alqueva) at Beja aerodrome was compared, showing a slight increase in the average number of days with fog during the winter (DJF), of about 4 days per winter after 2003. The numerical simulations for the case studies also show that only in winter cases the impact was visible, verifying a diversity of influences, confirming that, depending on the direction and wind speed, different effects may become dominant, causing different fog placement patterns. The fog duration over the reservoir had a shorter duration in the simulations with Alqueva during December, suggesting that its existence inhibited the fog formation and preservation. In the situation of February there has been a slight increase in the fog duration over the Alqueva reservoir, possibly due to the weak flow and also because of lower air temperatures. In the summer cases there were no appreciable differences between the simulations with and without Alqueva. The Meso-NH represented well the selected fog events, verifying a good approximation between the observed ones and their modeling for the five selected events. However, it was found that low clouds were slightly overestimated in winter cases and underestimated after the dissipation of fog in summer cases.

Based on this study, it can be concluded that the Alqueva reservoir may have a direct impact on fog formation in the lake region and its vicinity. Depending on the conditions, their influence can be both positive and negative, in the covered area and its duration. It is important to mention that, with the construction of the Alqueva dam, there was also a regional development that changed the land. It will be necessary to review all ECOCLIMAP database for the region, specifically water surfaces and vegetation cover, to improve the numerical modeling, where the soil-atmosphere interactions are fundamental.

The Meso-NH has proved to be extremely important, because it allowed for describing the selected events in a satisfactory manner, enabling the identification of surface coverage and orographic effects in the analysis and prediction of fog formation and its evolution in Alentejo region.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper. The authors confirm that the received financial support mentioned in the "Acknowledgments" does not lead to any conflict of interests regarding the publication of this paper.

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